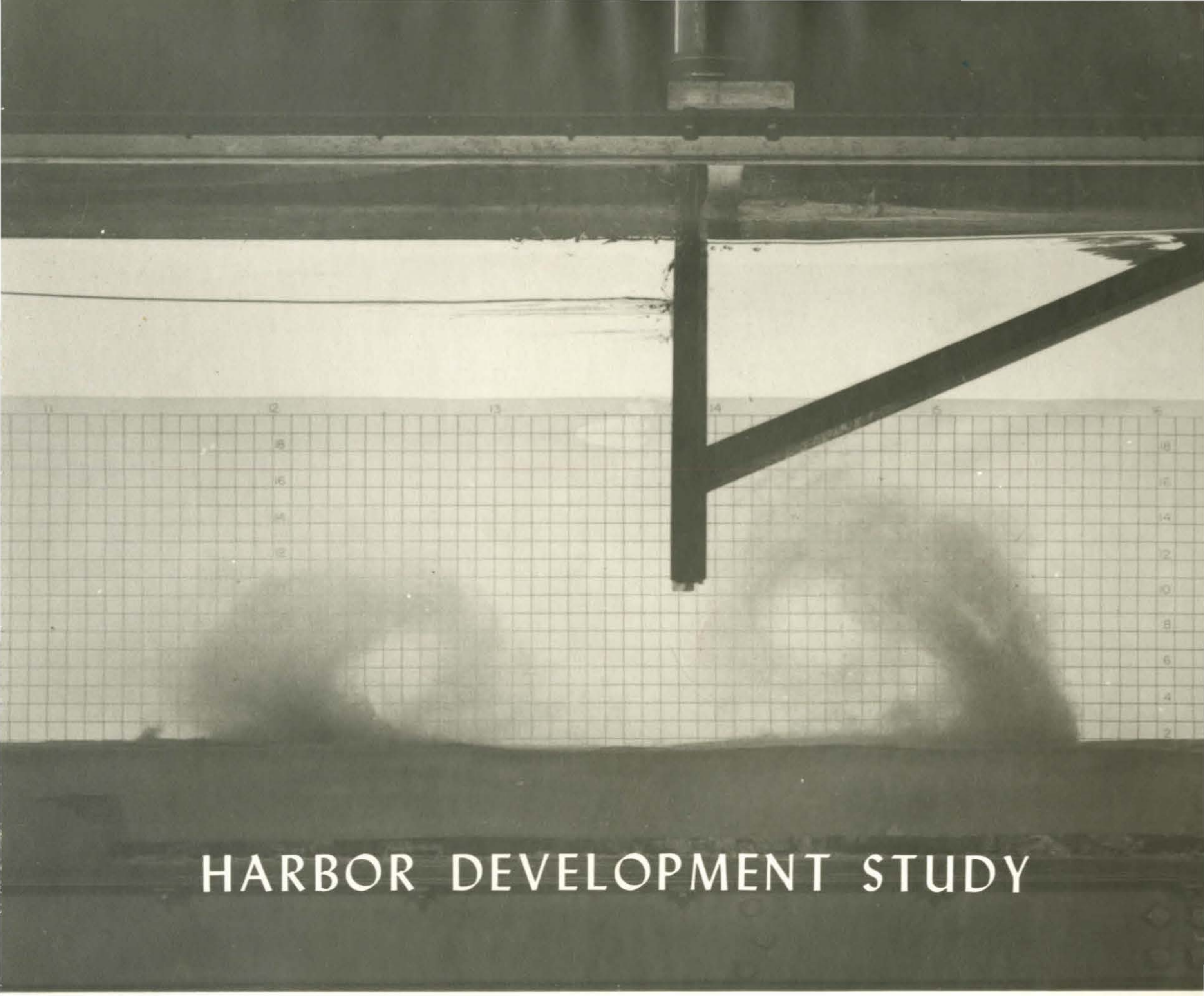

HARBOR DEVELOPMENT STUDY

INTERIM REPORT

January - July, 1952

CALIFORNIA INSTITUTE OF TECHNOLOGY
Hydrodynamics Laboratory, Hydraulic Structures Division

Department of the Navy Contract NOy-12561

DEPARTMENT OF THE NAVY

BUREAU OF YARDS AND DOCKS CONTRACT NOy-12561

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Interim Report for January - July 1952

Hydrodynamics Laboratory
Hydraulic Structures Division
California Institute of Technology
Pasadena, California

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The Cover

The cover photograph illustrates the initiation of scour under a vertical barrier as observed in experiments described in Part IV of this report. It is seen that sand scoured from the region immediately under the barrier is thrown into suspension a short distance on either side of the barrier, and is deposited there.

I. INTRODUCTION

This report summarizes experimental and analytical work conducted in the Laboratory during the first half of 1952. During this period the first task of the current change order, the preparation of a manual of harbor design, was also accomplished.

Sections II and III of this report describe work done in connection with the second task assignment - the obtaining of further information concerning wave disturbances in harbors. The experimental part of this study was terminated for lack of time before positive results could be obtained. The study was nonetheless interesting and valuable since it pointed out the importance of further investigation of the stability of standing wave patterns in closed basins.

Sections IV and V describe initial phases of two-and three-dimensional studies of scour, a program undertaken in accordance with the general provisions of the third task assignment of the change order. These studies are to be continued until the termination of the current contract period, and have been proposed for further study in the pending contract extension proposal.

II. COMPUTED DISTURBANCE FACTORS FOR SQUARE AND RECTANGULAR HARBORS

Since publication of the Interim Report, December 1951, several additional harbors have been analyzed by the graphical method described in that report. The new harbors analyzed were rectangular with the prototype dimensions of 4200 x 6000 ft. and 5939 x 8484 ft. The latter harbor, it will be noted, has twice the area of the former. The smaller harbor was analyzed with a 3-wave length opening centered on the long side and with a 2-wave length opening centered on the short side. The 5939 x 8484 ft. harbor was analyzed with 2- and 3-wave length openings centered on the long side. For the smaller harbor where the opening is on the long side, four beach conditions were used (no beach, 750-ft, 2250-ft, and 3750-ft beaches). The beaches were centered in each case along the wall opposite the entrance and were assumed to absorb all the energy impinging upon them. For the larger harbor, which has twice the area of the smaller one, the beaches were enlarged proportionately resulting in beach lengths of 1060 ft, 3181 ft, and 5302 ft. For the 4200 x 6000 ft harbor where the opening is in the short side, only two beach concitions were analyzed (no beach and a 4200-ft beach completely across the side opposite the opening). The wave length used in all analyses was 385 feet. Each harbor was computed for approach angles of 90°, 60°, 45°, and 30°.

The results of the recent analyses, together with results previously reported, are summarized in Figs. 1 through 6. The disturbance factors shown are expressed, as customary, in per cent of incident wave height. The "coefficient of reflection", which was used in computation, was 85%. The disturbance factors given are for small areas located at the corners and at the quarter and half points of the sides.

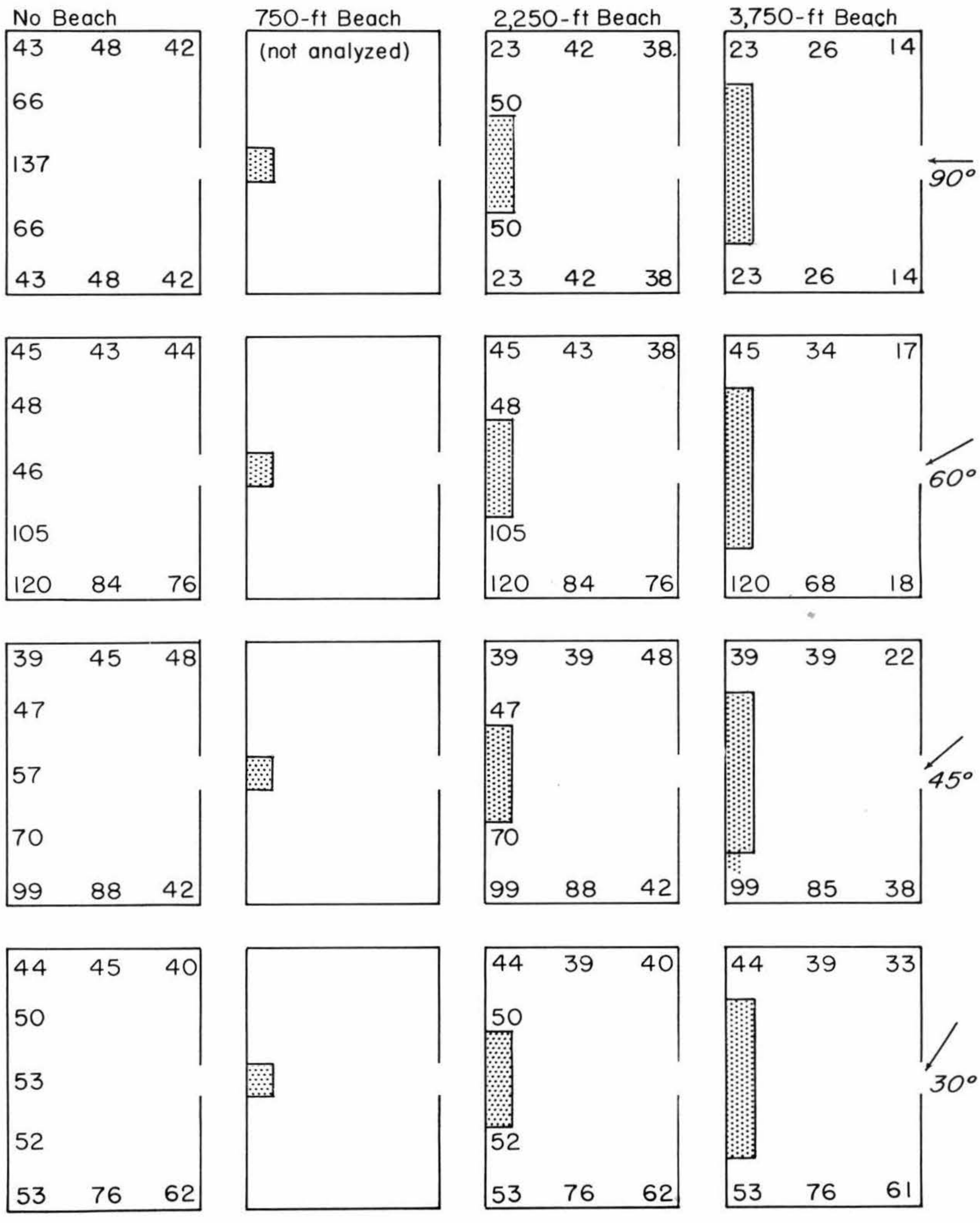

Fig. 1 - Computed disturbance factors for a harbor 4,200 ft by 6,000 ft
B = 2L L = 385 ft

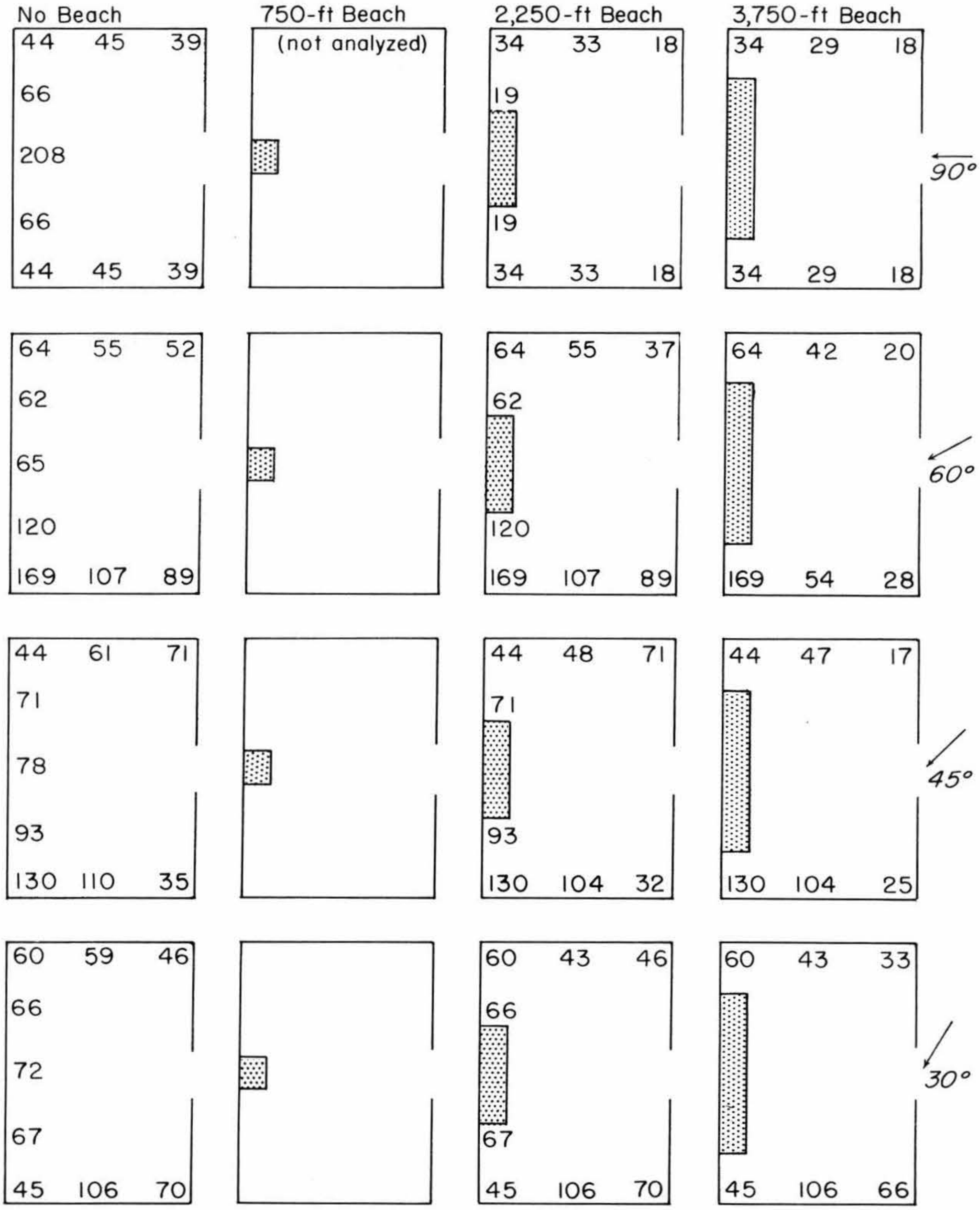

Fig. 2 - Computed disturbance factors for a harbor 4,200 ft by 6,000 ft
B = 3L   L = 385 ft

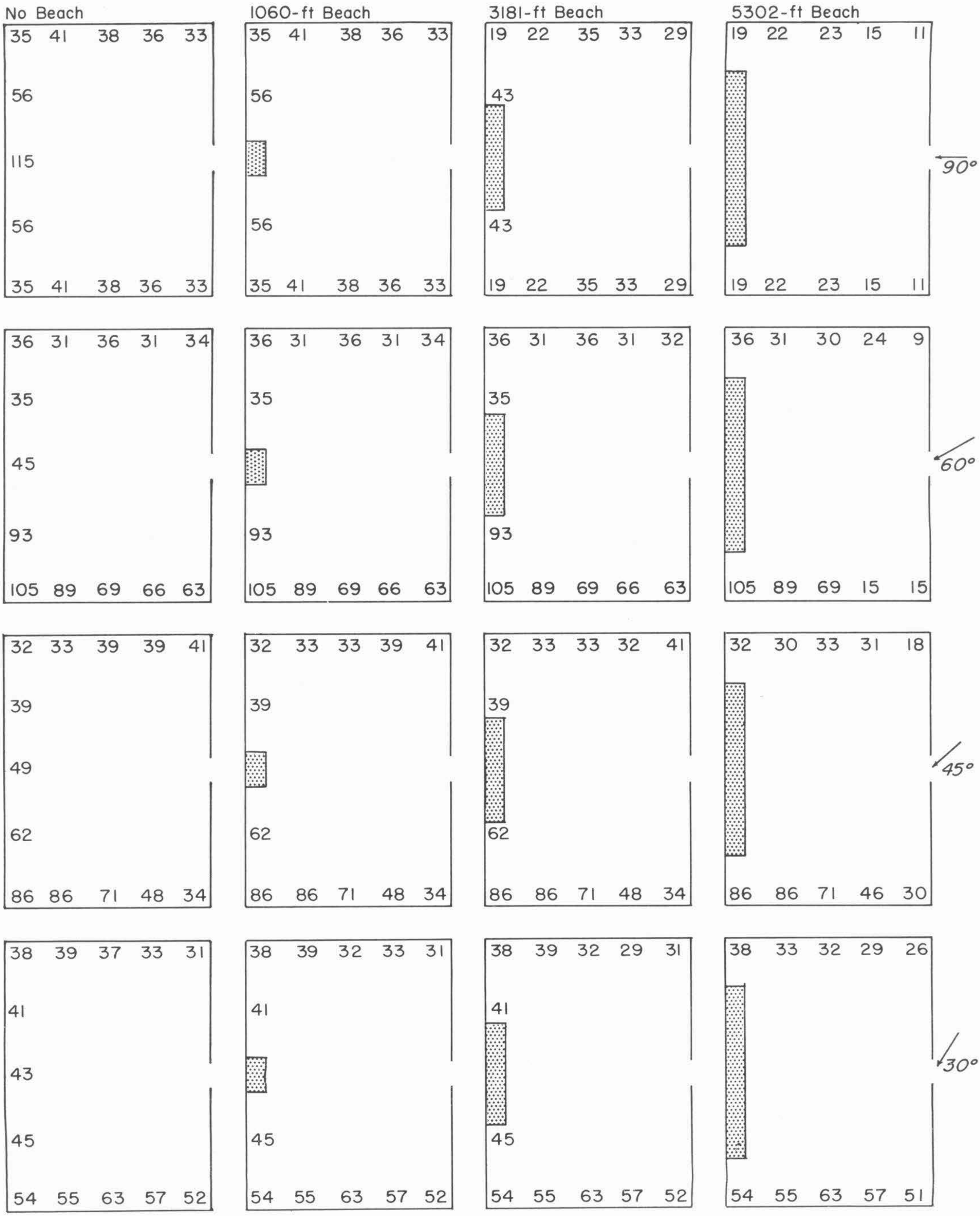

Fig. 3 - Computed disturbance factors for a harbor 5,939 ft by 8,484 ft
B = 2L L = 385 ft

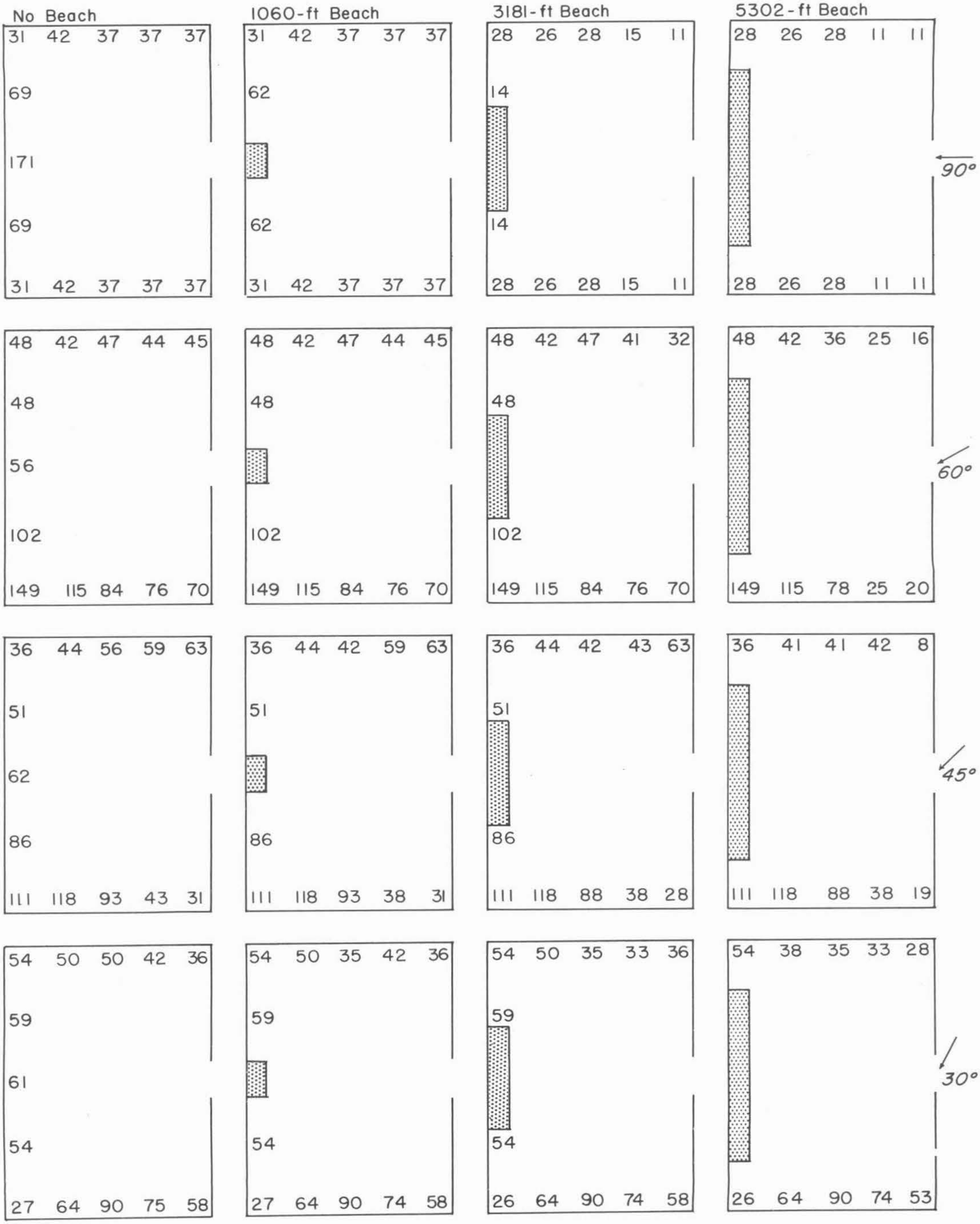

Fig. 4 - Computed disturbance factors for a harbor 5,939 ft by 8,484 ft
B = 3L L = 385 ft

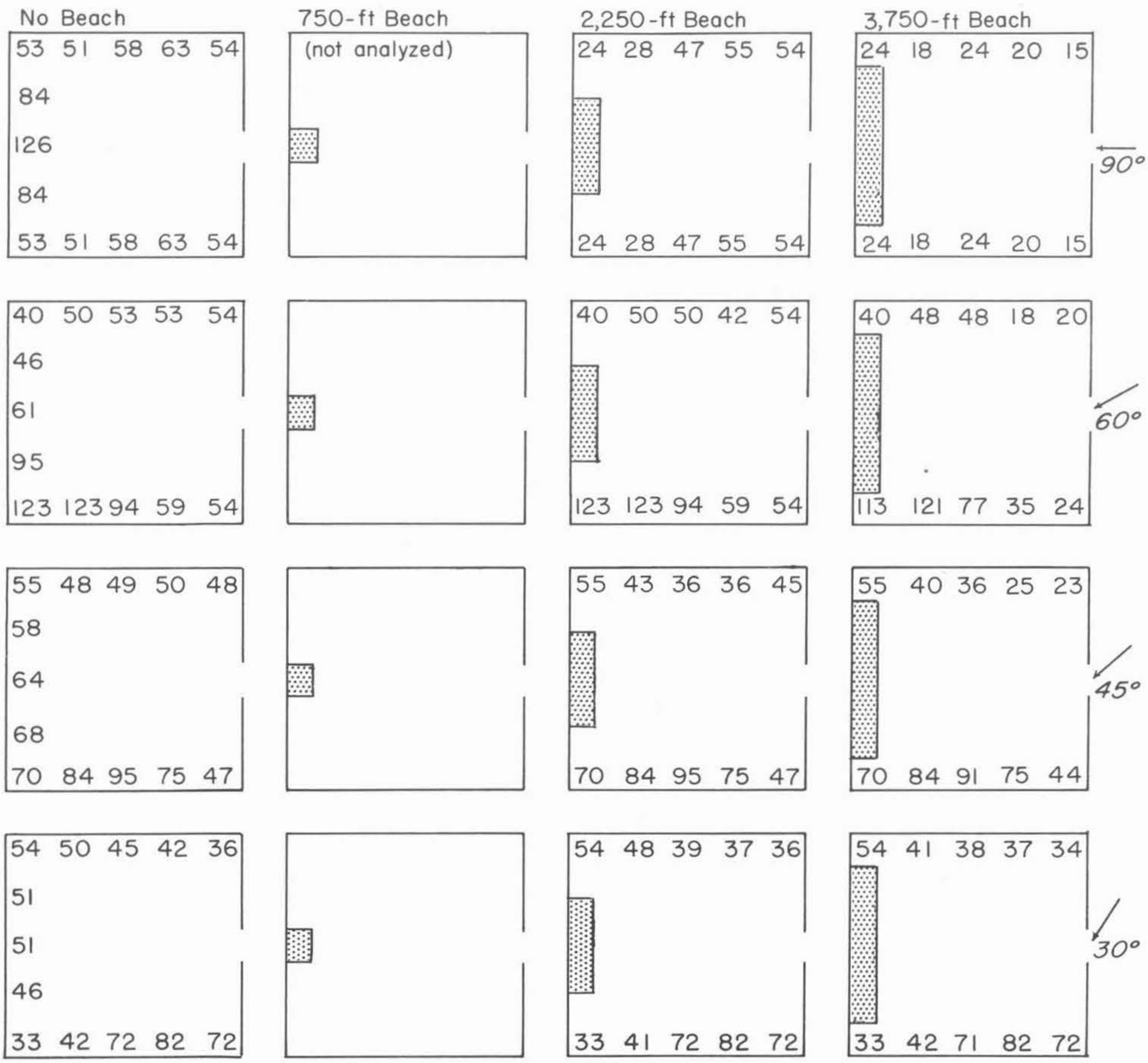

Fig. 5 - Computed disturbance factors for a harbor 5,020 ft by 5,020 ft
B = 2L L = 385 ft

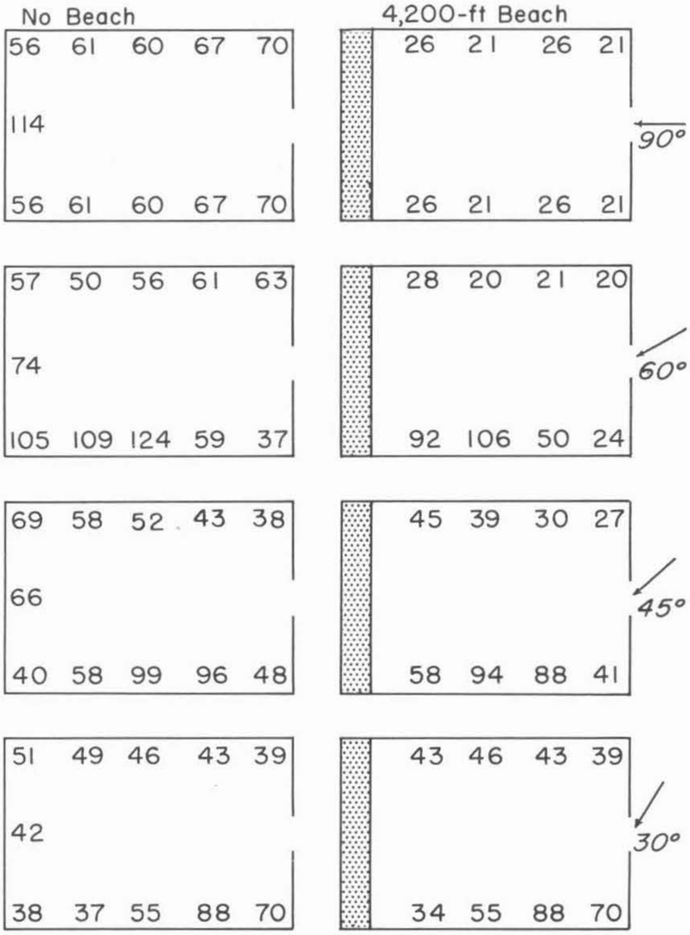

Fig. 6 - Computed disturbance factors for a harbor 6,000 ft by 4,200 ft
B = 2L L = 385 ft

Comparison of the different harbors verifies several interesting predictions which can be made about harbor size and shape. These predictions are:

(1) For a harbor with a given breakwater opening and shape, increasing the area will tend to decrease the wave disturbance at any relative location.

Note that corresponding values are lower in Fig.3 than in Fig.1 and also are lower in Fig.4 than in Fig.2.

(2) Increasing the opening for a harbor of given size and shape, will tend to concentrate more energy along the line of wave approach.

This is strikingly apparent by comparing the value for the location directly opposite the opening in the 4200 x 6000 ft harbor for wave approach of 90° with no beach and with openings of 2- and 3-wave lengths on the long side (Figs.1 and 2). It is noted here that for an opening change from 2 to 3 wave lengths, the central disturbance factor increases from 137 to 208 while adjacent values remain practically unchanged.

(3) The maximum disturbances are highest in the direction of wave approach.

This prediction is evident in all the cases presented.

(4) For maximum effectiveness beaches should be located normal to the main direction of wave propagation and should be as long as possible.

Note that in all harbors with a long beach, the values are considerably lower for waves approaching normally than for waves approaching obliquely to the beach. Note also that the smaller beaches have far less effect than the larger ones.

(5) For harbors where a major portion of the shoreline is wave absorbing, the minimum over-all disturbance within the harbor will be obtained when the opening is oriented so that a maximum expansion of the entering waves is possible.

Since the shoreline of the harbors is not largely wave absorbing, this prediction is hardly verified in these analyses.

III. HARBOR DISTURBANCE STUDIES

A. General

There is contained herein a description of the continuation of experiments dealing with reflection and absorption of wave energy at harbor boundaries. Experiments conducted with rectangular and square harbors were discussed in the Interim Report of December 1951. That report also describes the analytical method used for comparison with the experimental data. Since the issuance of the above report, considerable effort has been expended in a similar investigation for a trapezoidal harbor, a shape chosen to represent a more general harbor configuration. The square and rectangular harbors were identical in area, 25,200,00 square feet prototype, and the trapezoidal harbor likewise had the same area. The trapezoid was constructed as one half of a regular hexagon with 4406-ft long sides. It was necessary to transfer the study from the West basin to the Southeast basin, the shape of which was altered to adapt it to the experiments. Another change was that of scale, the first two harbors were constructed to a scale of 1:180 while the latter had a scale of 1:240. This with a model water depth of 4 inches, resulted in a prototype depth of 80 feet. It may be noted that prototype water depth is not an important factor in these studies.

Analytical determinations of the wave disturbance in various locations of the trapezoidal harbor, for a variety of wave approach angles and beach conditions were made, using the graphical technique outlined in the December, 1951, report.

Measurements of wave heights were at first made with the original electrical equipment, permitting the use of 17 measuring elements. The system was later converted to an electronic one, which embodies many important improvements over the original method and is similar to the system used with the 12-channel oscillograph, described in the

Interim Report for January - June, 1950. The change, however, permits the use of only 16 channels.

Two elements were placed seaward of the openings in all cases to measure the incident wave and, as customary, the measurements were expressed as percentages of this incident wave height. At first all the other elements were placed in one array, on 4-inch centers to cover an area of 8 x 16 inches (160 x 320 feet prototype) and also on 2-inch centers for a coverage of 4 x 8 inches (80 x 160 feet prototype). The array was placed successively in nine locations: on the quarter points of the wall containing the opening, on the mid-points of the opposite wall and the two walls joining the parallel walls and in the four corners. A rather intensive, local coverage was thus obtained. Measurements were also made in which simultaneous values at each of two symmetrical locations were obtained by the use of two arrays with seven probes each on 2-inch centers.

The results of this series of experiments were largely negative, in that consistent agreement with the analytical values, and in many cases, repeatability of identical separate runs were not obtained. These difficulties were especially severe for the basic configuration of 90° wave approach and no beaches, whereas some of the results with absorbing shorelines exhibited the good agreement with theory which characterized the earlier experiments with square and rectangular harbors. Because of the substantial ambiguity of the major part of the experimental work, neither experimental nor analytical results will be reproduced here, but the remainder of this section of the report will be devoted to the description of the experimental procedure and a discussion of some possible reasons for the anomalous results observed.

B. Techniques

Harbor and Wave Approach:

As before, the harbor was formed of 5-inch high sheet metal sections secured to the floor. The harbor was tested without a beach and with a beach along the entire side opposite the opening. The opening itself had a length equivalent to two wave lengths. The model wave length was 1.605 foot, corresponding to 385 feet in the prototype, with periods of 0.603 and 9.36 seconds respectively.

In addition to the many runs with a 90° wave approach, test runs were made in which the waves attacked the harbor with 30°, 45°, and 60° directions.

Pneumatic Wave Machine:

In order to work with a 4-inch water depth, it was necessary to construct a new pneumatic wave machine. This machine is of the same type as used in the Apra Harbor study except that the throat and chamber are modified to use with the smaller depth. The width of the machine is 20 feet. Tests made at 12 feet from the machine showed that the wave height along the 20-foot wave crests varied by only ± 8% from the median. This variation is considerably reduced when using only a small portion, approximately four feet, of the wave machine, as was done throughout the greater part of the investigation.

During the tests with the harbors, several entrance conditions were used in an attempt to gain even and symmetrical distribution of wave patterns at the entrance and within the harbors. The entrance conditions used with the pneumatic machine are listed below.

(1) The first condition was as used in previous studies which were conducted with the square and rectangular harbors. This entails the use of two wave splitters from the breakwater termini to the wave machine. This arrangement is shown in Fig.7. The waves in this figure are approaching the harbor at a 45° angle. It was noticed during some of these tests that cross-oscillation occurred between the splitters in spite of their close spacing. This caused uneven distribution at the harbor entrance and it is believed that this oscillation accounts for asymmetrical results inside the harbors.

(2) To overcome this cross-oscillation in the entrance channel, intermediate wave guides were placed between the two outside splitters. These guides were made of sheet metal and were fastened to a sheet of plywood supported in the horizontal plane with the guide hanging in the channel. A maximum of five intermediate wave guides were used. The guides extended from the wave machine to within one foot of the opening, or a total distance of 16 feet. Tests made at the entrance showed that the guides did not appreciably alter the cross-oscillation at the entrance itself. This may be due to the fact that reflections from within the harbor which reached the opening were still able to "bounce" off the guides and splitters.

(3) To overcome these unnatural reflections in the entrance channel all splitters and wave guides were removed and the 20-foot wave crests from the machine were permitted to run against a reflecting breakwater. Absorbing beaches surrounding the basin reduced the unwanted reflections. While this condition reproduces the prototype, except for reflections from the wave machine itself, the resultant pattern seaward of the breakwaters was still asymmetrical. This is possibly due to the fact that the waves produced by the machine vary slightly in height along the length of the crests.

Hinged Blade Wave Machine:

In an endeavor to eliminate the discrepancies in the results obtained with the pneumatic wave machine a small hinged blade wave machine was installed. The wave producing part is a sheet of half-inch plywood, 48 inches wide by 15 inches high. The back side is stiffened with angles. The blade is secured to the floor by means of three strong hinges, 17 feet from the harbor opening. A connecting rod is attached to the top center of the stiffening frame

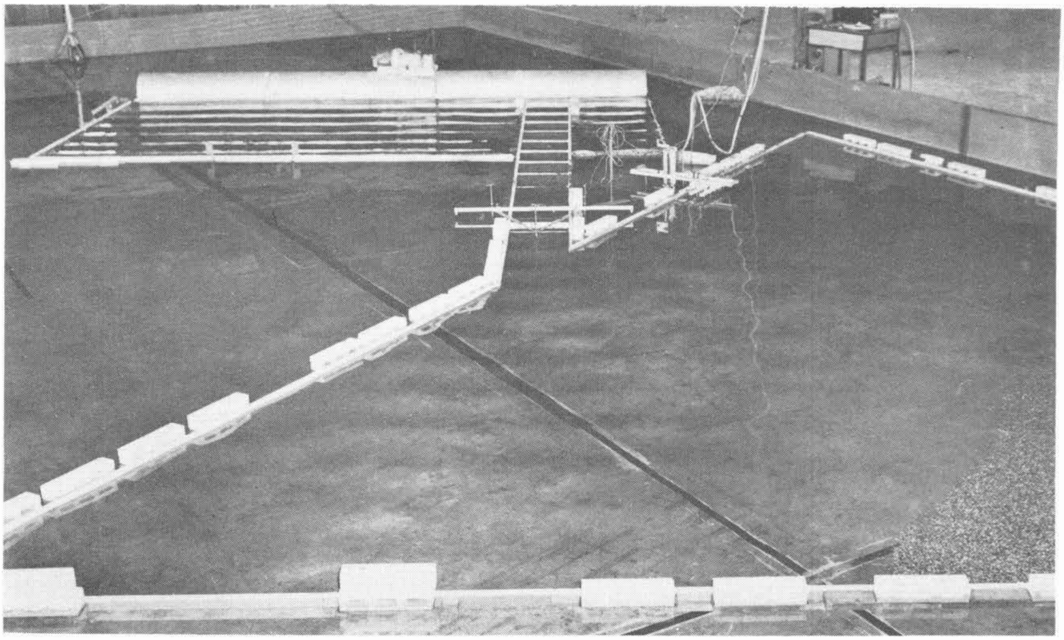

Fig. 7 - Arrangement for harbor disturbance study

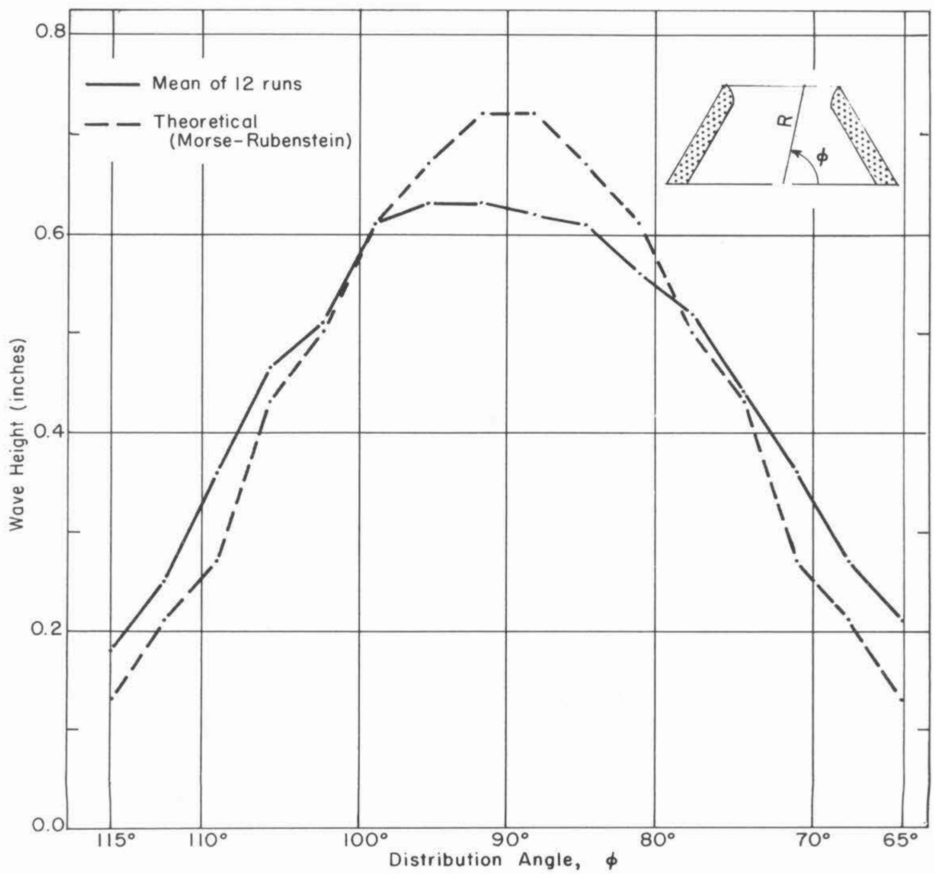

Fig. 8 - Plot of $H_{R\phi}$ vs. ϕ for a trapezoidal harbor

through a ball bearing and the other end is bolted through a ball bearing to a crank arm. Provision for sliding the rod against the crank arm is made, varying the effective length of throw of the arm and thereby the wave height. The arm is secured to the drive shaft of a 3/4 H.P. vari-drive motor, which permits variation in the period of oscillation. A gravel beach behind the blade is used to damp out unwanted waves.

Several entrance conditions were employed in the investigation with this machine, which was used only with a 90° wave approach.

(1) Two wave splitters were run from termini of the breakwater and stopped short immediately in front of the wave machine. This method did not eliminate the cross-oscillation in the entrance channel.

(2) Intermediate wave guides, as used with the pneumatic machine were employed, but again, improvement was not noticeable.

(3) The wave splitters and guides were removed, except that very short wave splitters were installed so that the hinged blade rocked between them, providing merely sufficient clearance to prevent scraping between blade and splitter. These splitters extended forward of the blade approximately four inches. In contrast to the splitters connected to the breakwater termini these short splitters permit the wave crests to expand by diffraction while not subjecting them to the effects of cross-oscillation. The distance from the wave machine to the harbor opening is sufficiently large to permit the segment of the crest intercepted by the openings to approach the harbor essentially as a uniform plane wave. This was verified by tests run at the harbor entrance. The entire area seaward of the harbor, including the greater part of both breakwater arms, was lined with gravel beaches. The "forebay" thus created contained no reflections not present in the prototype except those from the hinged blade. The short length of wave generator approximates a "point source" of waves. Therefore, of the total wave energy reflected out of the harbor opening but a small portion reaches the wave generator and is re-reflected.

(4) The waves were generated as in (3) above except that the short splitters were removed also. This appeared to have little effect on the wave generation.

Entrance condition (3) with the hinged blade appeared to be the best method of generating waves for this kind of a study. It was, therefore, used exclusively in the latter part of the experiments.

It should be stated, parenthetically, that several attempts were made to construct a "wave filter" for use in conjunction with the wave machines. The purpose of the filter was to eliminate re-reflections from the machine. It was determined, however, that construction of a workable filter was not feasible for the experiments, and the later development of the "point source" wave generator made a filter unneccessary.

Disturbance Measurements:

Measurements of wave height at selected locations in the harbor were made by means of electrical conductivity elements arranged in arrays to sample a finite area of water surface.

In a basin characterized by disturbances of the standing wave type, the amplitude of vertical water motion is a function of location as well as time, and the maximum amplitude can vary greatly between points which are close together in terms of the wave length of the disturbance. For example, in the simple case of a standing wave produced by the reflection of plane waves from a boundary parallel to the wave crests, nodal and antinodal lines, between which the amplitude varies from zero to a maximum, are located one-quarter wave length apart parallel to the boundary. In the more general case, which may include curved wave crests, multiple reflections, and oblique incidence to the reflecting boundaries, nodal and antinodal points are spaced in similar close proximity.

A sampling technique as described in the opening paragraph is, therefore, essential in order to obtain some measure of the overall disturbance in a small area. It is obvious that the accuracy of measurement depends greatly on the spacing of the sampling points. This requirement, however, must be balanced against the necessity of using a large enough sampling area to be meaningful (at least of the order of a ship's length), and the practical limitation on the number of measuring channels available.

The element spacing first used was 4", or about 1/5 wave length. This permitted a sampling area of about 1 x 1/2 wave lengths. In the effort to improve sampling accuracy, the spacing was reduced to 2", or about 1/10 wave length, at the sacrifice of sampling area, which became 1/2 x 1/4 wave lengths. For simultaneous measurements at symmetrical harbor locations, element spacings of 2" in a single-line array were used.

Techniques similar to those described above have proven to be adequate in previous studies in this Laboratory, whereas they failed in many of these experiments to yield consistent data. As will be discussed in more detail later, the current difficulties are believed due in part to the much more complex standing wave pattern characteristic of the undamped trapezoidal basin studied, with the result that the sampling techniques were inadequate.

C. Results

Description:

In reporting disturbance data for small areas of a harbor, it is considered desirable to accentuate the occurrence of large disturbances, since such disturbances are apt to be the cause of trouble in the prototype. Accordingly, it has been the practice of this Laboratory in recent years to report disturbance measurements in terms of the average of the highest one-third readings obtained from the individual elements of a sampling array. The choice of the highest one-third is based on the similar established practice in the forecasting of ocean waves.

In previous experiments utilizing this technique (i.e., the experiments with square and rectangular harbors, and the Mayport Model Study) it has been a relatively straightforward procedure to establish a time interval subsequent to the start of a run at which steady-state conditions obtained, and to determine the highest one-third traces on the oscillograph record of wave height element output. In some instances, as mentioned in the Mayport Model Study report of December, 1951, trouble has been encountered due to the occurrence of beat phenomena on some or all of the wave traces. The existence of such beats makes it difficult to establish whether a steady-state condition has been reached, since the beats on individual traces of a record do not necessarily occur simultaneously.

In the experiments with the undamped trapezoidal harbor, especially with 90° wave approach, beats of a magnitude never before encountered at this Laboratory were the general rule at all locations studied in the model. In addition, at least as described by the imperfect sampling technique available, the beat phenomenon exhibits a high degree of randomness, affecting differing number of elements in varying degrees during the course of a run or for separate identical runs at a given location. A variety of technique modifications were investigated in the effort to obtain reproducibility: the wave records were read at varying times (at the maximum beat without respect to time, at a fixed time without respect to beat, the average of extreme beats was obtained), the length of runs was increased, the number of duplicate runs was varied from three to six to twelve. None of these measures increased the consistency or reproducibility of the results.

With 90° wave approach, symmetrical behavior should be expected in the basin. Simultaneous measurements at symmetrical locations indicated the beat phenomena at such locations to be in phase, but the maximum amplitudes were not usually equal and frequently varied widely.

Some Checking Experiments:

The method of generating waves was first blamed for the difficulties encountered. The technique of using parallel wave splitters between the basin entrance and the wave machine was especially considered, since the channel so formed may be subject to cross-oscillation or longitudinal surging, and so influence conditions within the basin. It could not be proven that the splitter technique is entirely unsuitable but at any rate the "point source" wave machine operating in a completely damped forebay assured nearly ideal entrance conditions.

As a check on the uniformity and reproducibility of the waves produced by the "point source" generator, fifteen elements were arranged on 4" centers near the basin entrance in a line parallel to the wave machine blade. A temporary beach placed behind the elements prevented reflections from the breakwater. Eight runs were made and the results are considered very satisfactory. The averages of the fifteen elements varied only between 0.62 inch and 0.66 inch for the eight runs.

An experiment was performed to test a hypothesis that the asymmetrical behavior of the basin was in part due to the asymmetrical distribution of energy along the diffracted wave crests inside the basin. Absorbing beaches were placed along the two non-parallel sides of the trapezoid and the measuring elements were arranged along the side opposite the opening, one-half inch from the wall. The waves recorded were, therefore, subject to but a single reflection, and the results can be assessed in terms of diffraction theory by assuming a reflection coefficient (taken as 90%). Two series of runs were made; six runs with eleven elements on 20" centers along the wall and five elements equally spaced in the entrance, and twelve runs with sixteen elements on 12" centers along the wall.

The analysis of each such run showed the suspected asymmetry in varying degree. In other words, plots of wave height against element location for each run were quite similar in shape, but the positions of the maximum were displaced to right or left of the theoretical location (basin centerline) in a random manner. It is difficult to say if the degree of asymmetry of the wave fronts as shown by these experiments is such as to constitute a major or minor part of the asymmetry observed when the additional complications of multiple reflections are present in the undamped basin. It is possible, of course, that the asymmetry observed after diffraction is entirely due to very slight asymmetry in the incident waves which could not be detected from the records of the control elements at the entrance.

An additional result of this experiment was the verification of the wave heights predicted by the Morse-Rubenstein diffraction theory, on comparison with the averaged results of all runs.

This comparison shows that the percentage deviation from the theory is greatest at the points which are farthest from the center of the wall. This, however, is not at all surprising, since these values are also the lowest of the set and even a small absolute difference will result in a relatively large deviation percentage-wise. These low values occur between 64 and 71 degrees and 116 and 109 degrees, measured from the breakwater about the center of the opening. The polar plot of intensity factors for 90° approach and two wave length opening (Interim Report, December, 1951, Fig.5) shows an indentation at 60 degrees and a symmetrical one at 120 degrees. This indicates that even a very slight shift in the wave pattern will result in a considerable change in wave height in this sector. The agreement in the remaining sector, approximately 38 degrees (from 71° to 109°) is very good. It should be borne in mind that the runs discussed above were made with beaches in the harbor and before re-reflections influenced the wave heights. Figure 8 shows the averaged observed and the theoretical wave heights.

Conclusions:

It may be concluded that because of the pronounced beating characteristic of the water surface disturbances observed in the trapezoidal basin, especially with 90° wave approach, ordinary sampling techniques are inadequate for the determination of representative disturbance levels at particular locations in the harbor.

Beat phenomena arise due to the interaction of two or more waves with slightly differing wave lengths. Since the generated wave period and the water depth are constant, it may be wondered how waves of differing length can be present in the basin. At least two sources of such variability are, however, present. One of these is the second-order effect of wave height on wave velocity. This factor is present since the waves are known to lose energy, hence decrease in height, in traveling and reflecting within the basin. Even though the variation in wave velocity, hence in wave length with the necessarily constant period, is very small, the effect is cumulative. Thus, with a velocity difference of 1%, a one-quarter wave length phase shift will result after 25 wave lengths of travel, which is about twice across the basin. The second source of wave length change is that due to diffraction. If the wave velocity were everywhere equal along a diffracted wave crest, the crest alignment would consist of a straight segment equal in width to the basin opening, connected to the breakwater by circular segments. Since in fact the crest alignment becomes semi-circular at relatively short distances within the harbor, it is apparent that the wave velocity in the region of the center portion of each diffracted crest is greater than that at the shoreward ends of the crest. As the different segments of crest reach a reflecting boundary and re-traverse the harbor, ample opportunity exists for the interaction of waves of slightly differing length.

It might still be expected that reproducible steady state conditions would obtain in the basin even with the presence of pronounced beating. It is believed that the results of the experiments in this regard are due to a combination of the particular basin shape studied and the inadequate sampling methods used. As previously mentioned, the diffraction diagram for a two wave length opening shows a pronounced indentation in the directions of 60° and 120°. These directions coincide with intersections of reflecting boundaries in the trapezoidal harbor studied. Thus, a slight deviation in the pattern of wave crests emerging from the harbor opening will result in a large deviation in the height of waves reaching and reflecting from the two distinct boundaries, hence the pattern of reflections from the shoreward corners of the basin are greatly affected by small deviations in the initial diffraction process. This situation is aggravated by the admittedly inadequate measuring apparatus currently available, which cannot sample a large enough area to pick up gross changes in standing wave patterns with fine enough element spacing to fairly sample the standing wave amplitudes.

Finally, it should be stated that the experimental philosophy is fundamentally sound, since, speaking of the basin as a whole, steady state conditions do obtain. This is shown by the facts that the disturbance in the basin does not increase without limit and that the control elements at the harbor entrance show no long period oscillation of energy into and out of the basin. The lack of success in obtaining useful data in this case must be ascribed primarily to the singular combination of basin shape and diffraction characteristics, since the other complicating factors have been present in other, successful, experiments. The difficulties encountered emphasize the limited capacity of accepted measuring techniques in situations where a high degree of variability of disturbance is encountered.

Future Program:

Although no further work on the harbor disturbance study was contemplated for the coming contract period, it is felt the above described experiments pose some questions of a general nature which should be investigated. It is hoped, therefore, that from time to time opportunity will be afforded for further study of the stability of the energy front resulting from diffraction through a gap, and for critical study and improvement of measuring techniques.

IV. TWO-DIMENSIONAL SCOUR STUDIES

A. Equipment and Techniques

When a rigid bulkhead, fixed vertically in the water a finite distance above a sand bed interferes with the free progress of a wave, the distorted particle motion which results gives rise to erosion under the bulkhead. A preliminary photographic study of this scour has been completed in the Laboratory's new elevated channel. While this study was qualitative in nature, it indicated some of the incident wave conditions and magnitudes of clearance required to cause varying degrees of scour, and will serve as the basis for planning future investigations of a more quantitative nature.

Channel:

Since the channel and wave machine used are new and have not been used in previous experiments, it is well first to describe them in relation to the equipment and techniques employed. The channel is 100 feet long, two feet wide and three feet deep, and its bottom stands two feet above the floor. Near the middle of the channel length is a section eighteen feet long where the channel wall on both sides is formed by half-inch aquarium glass for convenience in taking photographs and for visual observations. The rest of the channel wall is assembled in five-ft. sections made of 3/16 in. steel plate with vertical stiffeners of 2 in. x 2 in. x 3/16 in. angles, and with horizontal reinforcements of 3 in. x 3 in. x 3/16 in. angles at top and bottom. These sections are bolted together and to the bottom, which rests on pipe sections spaced ten feet apart. Additional rigidity is obtained by the use of plate sections at the ends, and by tie-rods spanning the top of the channel at five-foot intervals. Two wave absorbers are used, one behind the wave machine and one at the far end of the channel. These are removable excelsior-filled units whose seaward surfaces are sawtoothed and have slopes of about thirty degrees. Tests indicate that they possess about the same degree of energy dissipation as the sloping plywood beaches which have previously been used.

Wave Machine:

The wave machine is of the inverted ballistic-pendulum type, similar to the machine which has been used in the four-foot channel for previous two-dimensional studies. It was designed to produce a full range of waves from deep water to shallow water types. In two feet of water it is capable of generating a maximum wave about 32 feet long and nine inches high. For a wave of a particular length the blade may be adjusted to impart particle motion to the water which is of the proper relative horizontal dimensions at surface and bottom. For a pure deep water wave, for example, the blade rocks about its bottom, and for a very shallow water wave the blade assumes a purely translational back-and-forth motion. The exponential curve which normally forms the envelope of the particle orbits from surface to bottom is then approximated by a straight line, but the approximation is sufficiently close that the generated wave is enabled to assume a stable form reasonably close to the wave machine.

The prime mover is a 3/4- horsepower Varidrive having a continuous range of speed adjustment from about 15 to 115 rpm. The speed control, of course, determines the period, and consequently the length of the generated waves. The length of the crank arm is continuously variable from zero to twelve inches. A manually operated clutch makes it possible to disengage the blade from the motor so the speed of the motor may be adjusted or checked without adding energy to the channel water. Rubber wipers on each side of the blade and a fillet under the blade cast of concrete to a pre-computed profile reduce to a minimum the amount of blow-by between the blade and the sides or bottom.

Bulkhead:

The bulkhead which served as a barrier in this experiment was made of $\frac{1}{2}$-in. plywood reinforced by a framework of welded angles on the downstream side. It was clamped at the top to one of the tie-rods in the glass section of the channel and braced by means of angles extending to an adjacent tie-rod, making the bulkhead reasonably rigid and capable of being adjusted in clearance with the sand-bed. Adjustable strips of wood covered with rubber eliminated any passage way for energy at the sides of the board, and helped to avoid damage to the glass.

Sand:

The sand used in this scour study occupied a depth of six inches and a channel length of fifty feet centered at the glass section. Concrete fairing pieces, triangular in longitudinal section, retained the sand in position and provided a gradual depth reduction from $2\frac{1}{2}$ feet at the wave machine to two feet over the sand. A scale of 1:20 was adopted in order that this two-foot model depth would represent the prototype depth of forty feet which has been used in other two-dimensional studies. In this section of the report dimensions are given in terms of prototype dimensions.

The sand was Del Monte White Sand-Quartz, obtained from the Brumley-Donaldson Co., Los Angeles, California, with the following screen analysis:

U.S. Sieve No.	% Retained
40	12.5
50	49.8
70	35.5
Pan	2.2

Selection of this particular sand was influenced by the results of the experiments conducted at the University of California on various types of sands. The first of these experiments[1] indicated that Del Monte White possessed the proper range of grain sizes to form stable beach profiles in the model similar to those in nature. The second, using this particular sand was a study of sand accretion and erosion in the presence of various types and arrangements of groins[2].

Techniques:

The barrier was installed in various locations relative to the sand bed, and for each location incident waves of two different periods were generated. The first setting of the board was such that the lower edge was submerged the maximum distance below the level sand which still permitted scour to occur under the board. The next setting was with the bottom of the board just touching the levelled sand bed. Successive locations in terms of prototype dimensions were at clearances of 3.3, 6.7, 10.0, 13.3, 16.7, 20.0, 25.0, 30.0 and 35.0 feet. The two wave periods which were employed were seven and twelve seconds, producing wave lengths of about 200 and 400 feet. The incident wave height in each case was about seven feet, the maximum height which, with the reflected energy, did not splash water over the sides of the channel.

Photographs were made using Edgerton flash lights on the near and far sides of the channel. For each board setting and incident wave condition a picture was taken first with still water and smooth sand. The next was taken as the first sand motion was noted, which time was taken as the origin of the time scale. Thereafter, pictures were taken at intervals which depended on the extent of sand activity. Normally, the lapsed time periods were 2.3, 4.5, 9.0, 13.5, 18.0, 22.5, 33.7, and 45.0 minutes, and if scouring activity still persisted, additional pictures were taken. The wave machine was left running continuously until either the sand reached a stable profile or until, as in a very few cases, the waves ate entirely through the sand to the bottom of the channel.

After each series of runs was made it was necessary to level the sand as carefully as possible. When filling in the scoured-out depression the sand was tamped gently to make it as firm in that area as in other parts. Otherwise the decreased apparent specific gravity of the sand would have resulted in a more rapid erosion than normal.

B. Preliminary Results

The pictures which were taken in the course of this study reveal something of the effect of the wave parameters and the bottom clearance on the scouring process. Fig. 9 shows a sample of these pictures, illustrating the progress of sand scour when the bottom clearance was ten feet and the wave period was seven seconds. Much information has been obtained from examining these pictures and from observing the model in action.

(1) With the wave periods and heights employed, the energy of the incident waves used was insufficient to set up scour when the bottom of the barrier was submerged in the sand more than two feet.

(2) The first penetration of the sand bed adjacent to the submerged barrier was primarily a result of the difference in hydrostatic head between the two sides of the barrier.

(3) While this penetration of the sand bed was slow in occurring, once it had occurred, the opening quickly enlarged due to the flow of water through the depression.

(4) In all cases the wave height played an important part in the rapidity with which the opening enlarged, as did also the extent of horizontal particle-orbit motion near the bottom, which, for a given wave height, is a function of the wave length.

(5) For small clearances, the scour profile was nearly symmetrical about the extended line of the board.

(6) As the clearance increased the depression was formed farther shoreward. The sequence of pictures in Fig. shows the blasting action of the water which results in the displacement of the depression. It is not certain whether a displacement would occur if the channel were infinitely long. One result, however, is that there is a net transport of sediment in the direction of wave progress.

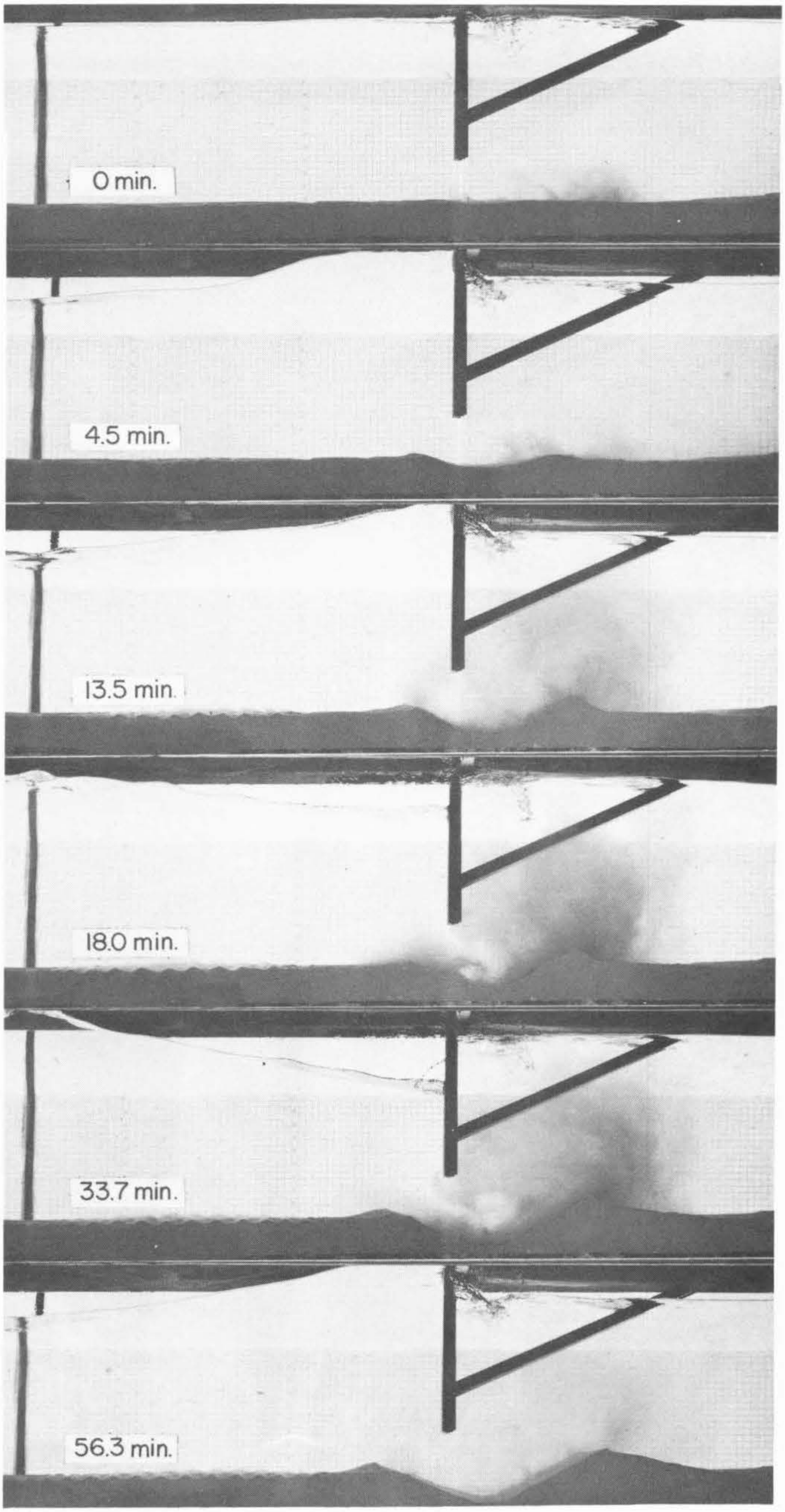

Fig. 9 - Erosion under a fixed rigid bulkhead, 10-ft original clearance, $\lambda = 200$ ft

(7) A very small amount of scour occurred for clearances as large as 35 feet.

(8) Reflection caused sand ripples to form, as one would expect, at areas a quarter wave length from the board, where nodes of the partial standing wave were located, and where the consequent particle motion was primarily horizontal. No ripples occurred near the antinodes.

Several problems are yet to be solved by later phases of this investigation. Chief among these questions is how much effect the finite length of the channel has on the scour process. A second is the effect of the direction of wave approach on the scour process.

V. THREE-DIMENSIONAL SCOUR STUDIES

A. Problem

There has existed for some time a need for the investigation of the stability of the footings of portable, gravity-type wave barriers (caissons). This Laboratory, accordingly, is currently beginning an attempt to model the problems involved. It is fortunate that a certain amount of prototype experience is available for a comparison of the test results.

The problem of scouring, in connection with portable, gravity-type wave barriers, manifests itself primarily by its effect on the displacement or dislocation of the barriers and possibly on the life of the structure itself. In the first instance the scouring may cause the individual caissons to slip, in extreme cases even to overturn, and in the second to break apart if the scouring underneath the structure brings about an inadequate support.

The available prototype experience is based mainly on that with the "Phoenixes" towed across the English Channel in 1945 and installed at Arromanches Harbor, France. The program at the present time is based on making experimental runs with models of the Phoenix, in an effort to develop a usable empirical testing technique. If reasonable agreement can be obtained with the available prototype Phoenix data, other structures will be investigated.

B. Equipment and Techniques

Six Phoenix sections were built of transite to a scale of

1:60. It was considered essential to duplicate only the overall dimensions, omitting the stepped construction fore, aft, and at the sides. The model Phoenix is shown in Fig. 10 .

The experiments will be conducted in the West basin, 42' 7" x 90' 6". The basin is of the standard construction used by this Laboratory. The sea bottom is reproduced by Del Monte White sand, as described in Section IV. An area of 30' 10" x 27' 4" was covered with this sand to a depth of three inches. The sand bed is surrounded on three sides by gravel, the surface of which rises from three inches at the sand to 15 inches at the wall, having a slope of 1 on 6. It is expected that this material and slope will result in efficient wave damping, eliminating all reflections from the boundaries. A 20-ft. pneumatic wave machine, described in previous reports, is placed three feet from the sand and centered on the larger dimension. Along this side is placed a concrete wedge, two feet wide, which drops from a height of three inches at the sand to zero at the other end. It is hoped that this will result in a better transition of the waves. The gravel beach extends from each end of the wave machine to the side beaches so that no extraneous reflections will reenter the experimental area. Each of these short beaches is equipped with a duct to facilitate the filling and emptying of the basin. The six Phoenixes are centered on the sand bed so that the waves traverse over 22' 4" (1340 ft. prototype) of "ocean" before reaching the barriers. Water is pumped into the basin from the underground storage reservoir. The arrangement of the basin is shown on Fig. 11 . The Phoenix sections to be tested can be aligned in different directions to simulate other angles of wave approach.

The pneumatic wave machine being used is designed to produce waves in 12 inches of water so that the water depth at

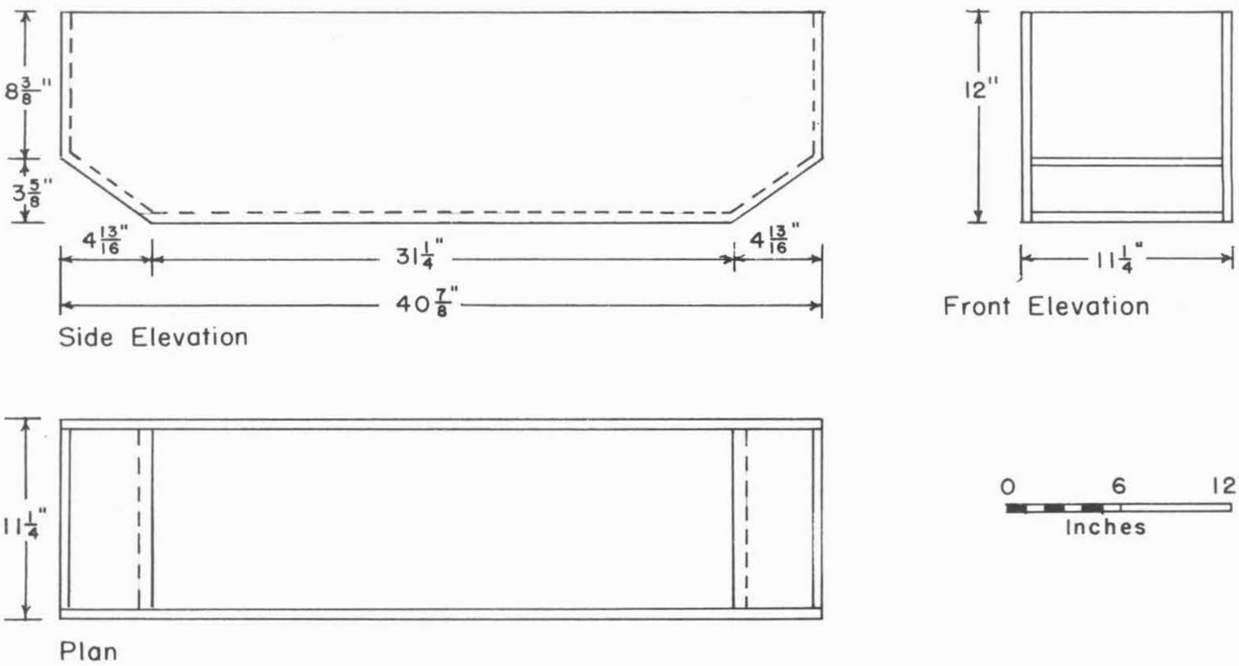

Fig. 10 - Phoenix model, scale 1:60

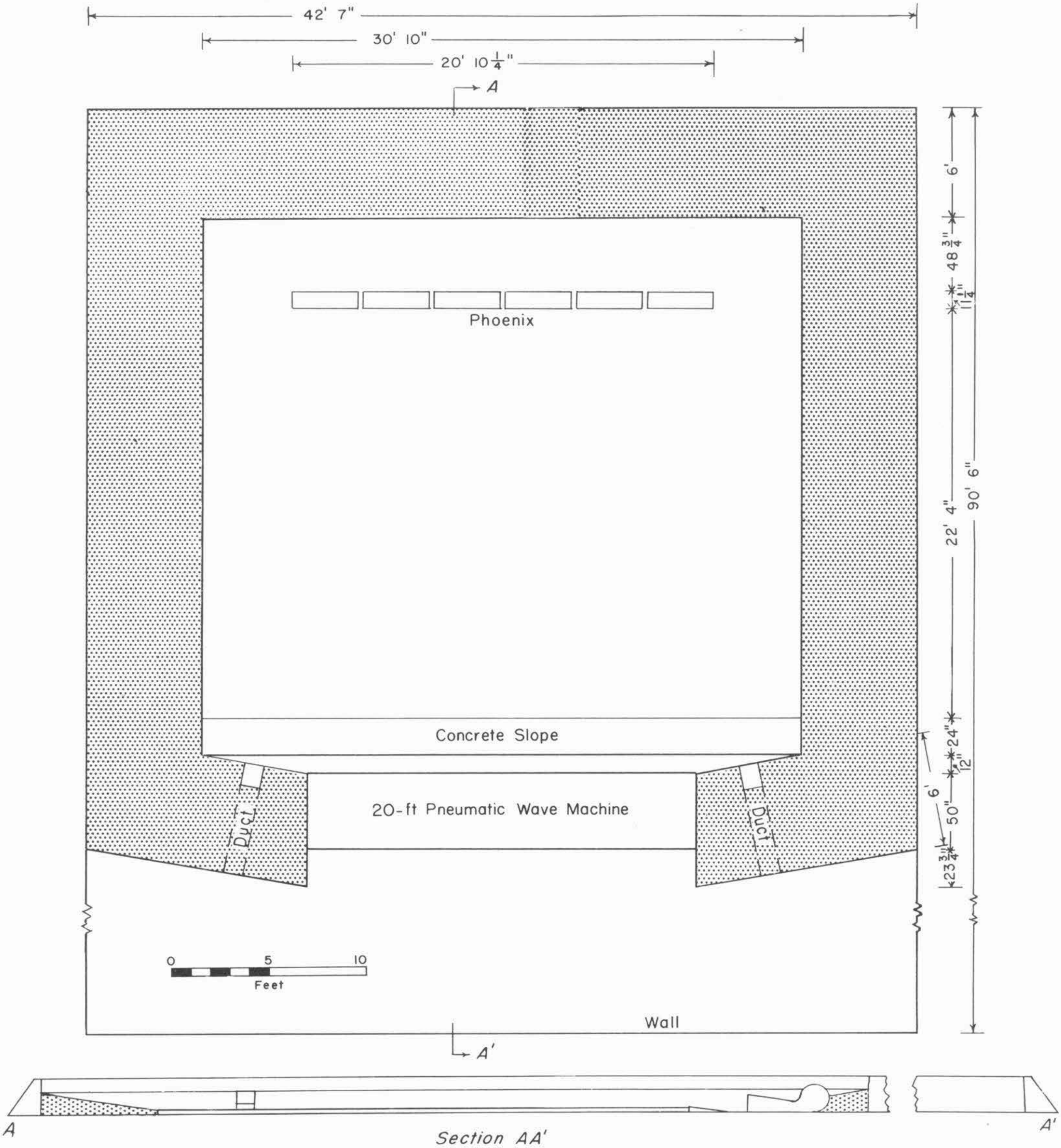

Fig. 11 - Movable-bed model basin

the model, allowing for the thickness of the sand, is 9 inches, corresponding to 45 feet in the prototype; 8-and 12-second waves will be reproduced, having lengths of approximately 260 and 425 feet, which, on the laboratory scale, will be 1.03 and 1.55 seconds and 4.35 and 7.10 feet respectively.

One-to two-inch high waves will be sent against the Phoenixes. The extent of scour will be evaluated qualitatively by photographic means during the first stages of the study. When optimum techniques for best modeling have been determined, quantitative scour measurements will also be made.

References

1. Shay, E.A. and Johnson, J.W., "Sand Studies in Two Dimensional Wave Motion", Series 14, Issue 5, Institute Engineering Research, University of California, Berkeley, November, 1950.

2. Shay, E.A. and Johnson, J.W., "Influence of Groins on Beach Stabilization", Series 14, Issue 6, Institute of Engineering Research, University of California, Berkeley, January, 1951.